

Life cycle assessment of native plants and marginal lands for bioenergy agriculture in Kentucky as a model for south-eastern USA

SETH DEBOLT*, J. ELLIOTT CAMPBELL†, RAY SMITH JR.‡, MICHAEL MONTROSS§ and JOZSEF STORK*

*Department of Horticulture, N-318 Agricultural Science Center, University of Kentucky, Lexington, KY 40546-0091, USA,

†College of Engineering University of California, Merced, CA 40546-0091, USA, ‡Department of Agronomy, N-200 Agriculture Science Center North, University of Kentucky, Lexington, KY 40546-0091, USA, §Department of Biosystems and Agricultural Engineering, Barnhardt Building, University of Kentucky, Lexington, KY 40546-0091, USA

Abstract

The Brookings Institute analysis rate both Lexington and Louisville, Kentucky (USA) as two of the nation's largest carbon emitters. This high carbon footprint is largely due to the fact that 95% of electricity is produced from coal. Kentucky has limited options for electric power production from low carbon sources such as solar, wind, geothermal, and hydroelectric. Other states (TN, IN, OH, WV, and IL) in this region are similarly limited in renewable energy capacity. Bioenergy agriculture could account for a proportion of renewable energy needs, but to what extent is unclear. Herein, we found that abandoned agricultural land, not including land that is in fallow or crop rotation, aquatic ecosystems, nor plant-life that had passed through secondary ecological succession totaled 1.9 Mha and abandoned mine-land totaled 0.3 Mha, which combined accounted for 21% of Kentucky's land mass. A life cycle assessment was performed based on local yield and agronomic data for native grass bioenergy agriculture. These data showed that utilizing Kentucky's marginal land to grow native C_4 grasses for cellulosic ethanol and bioelectricity may account for up to 13.3% and 17.2% of the states 2 trillion MJ energy consumption and reduce green house gas emissions by 68% relative to gasoline.

Keywords: biofuel, cell walls, cellulosic biofuel, feedstock, GHG (green house gases), lignification

Received 20 March 2009; revised version received 8 June 2009 and accepted 1 July 2009

Introduction

Decreasing reliance on fossil energy will inevitably result in a shift in economic viability of related industries, and a growth of localized energy economies with the potential to revitalize rural communities. For these reasons and in an effort to realize energy independence, public opinion, and legislation will continue to place an emphasis on reducing fossil energy consumption and switching to renewable forms of energy to stem carbon emissions. Reports from organizations such as the Brookings Institute (2005) that rate Lexington and Louisville (Kentucky) as the nation's largest carbon emitters will pressure states like Kentucky where an extremely high carbon footprint is largely due to the fact that 95% of our electricity is produced from coal

(Energy Information Administration (EIA, 2007). Other states (TN, IN, OH, WV, and IL) in this region also derive a substantial amount of electricity from coal. As with many states in this region, Kentucky has limited options for electric power production from low carbon sources such as solar thermal, photovoltaic solar, wind, geothermal, and hydroelectric. Hence, bioenergy agriculture may be an avenue worth pursuing to reach renewable energy goals. Recent assessments of the 'carbon cost' from land use change (Searchinger *et al.*, 2008) suggest that cutting forestland (3.5 Mha) to grow bioenergy crops will accelerate climate change by emitting carbon currently sequestered within plant matter and soil (Piñeiro *et al.*, 2009). Furthermore, land use change from agricultural land used for food production converted into bioenergy agriculture poses a significant threat to global food security (Boddiger, 2007). Utilizing abandoned agricultural and mine lands for bioenergy

Correspondence: Seth DeBolt, e-mail: sdebo2@email.uky.edu

agriculture could overcome both problems and Kentucky and many states in the southeast have high abandonment rates (Campbell *et al.*, 2008). However, before this study, it was unclear how much land was marginal, defined as previously used for mining or agriculture and moreover has not yet gone through secondary ecological succession, which is then classified as forestland. Life cycle assessment (LCA) and bioenergy potential analysis are currently needed to assess regional potential for renewable forms of energy using marginal land. Failing to adequately calculate the cost of land use change, resulting in increased carbon emissions, will pose significant risk to scientific validity and public perception of policy level decision making on the bioenergy issue.

Analyses show that marginal land used for bioenergy agriculture could account for up to 8% of the world's energy from biomass (Campbell *et al.*, 2008). LCA must also take into account lower expected yield potentials on marginal land relative to agricultural land (Tilman & Downing, 1994; Haberl *et al.*, 2007). But, utilizing marginal agricultural, abandoned or reclaimed mine land, and woodland areas has unique challenges related to establishing, growing, harvesting, and transporting the crops from the land to an end user. The assessments made herein are based on cellulosic feedstock rather than corn ethanol, although we note that cellulosic feedstocks will also undermine food security if they are grown on prime agriculture lands and therefore focus on marginal land. To begin moving in the direction of resolving these issues, this project addresses a life cycle roadmap for how bioenergy agriculture could fulfill a component of renewable energy needs and what the cost of production and consumption are relative to current fossil energy.

Materials and methods

Data sources

Net energy balance of prairie biomass was generated based on data derived from various sources and are summarized in supplemental Table 1 (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET Wang *et al.*, 2007), Tilman & Downing, 1994; Farrell *et al.*, 2006; Tilman *et al.*, 2006; Haberl *et al.*, 2007, Energy Information Administration EIA, Kentucky State Energy Use Table 2007, Kentucky Mine Mapping Information System 2008, Kentucky State Abandoned Mine Report 2008, and a 7 year collection of crop yield and input data collected for multiple entries of three different native perennial grass species at Spindetop Research farm in Lexington, Kentucky 38.051°N, 84.061°W (elevation 981 ft) (agronomic analy-

sis: Stork *et al.*, 2009). Species used were multiple entries of eastern gamagrass (EG) (*Trispicum dactyloides* L.), switchgrass (SW) (*Panicum virgatum*), and big bluestem (BB) (*Andropogon gerardii* Vitman). Where possible, this regionally collected and verified data was preferentially used for LCA and modeling. Briefly, these plots were randomized in a block design with four replications and $4.5 \times 1.5 \text{ m}^2$ (with 1.5 m perimeter comprising each entry) sites were established in the year 2000 into a well-drained Maury silt loam soil (fine mixed, semiactive, mesic Typic Paleudalfs).

Soil analysis. Soil analysis data was used to determine what mine lands might be contaminated with that could affect yield of energy crops species and to estimate required input needs for the natural production model on a site, which reflects local constraints on abandoned land, climate, and soil types. Values for soil N, P, K, Zn, Cd, Mg, Ca, Pb, Mo, Ni, and Cr were obtained from independent soil analyses from mine sites and abandoned agricultural lands in Kentucky. Methods for analysis were derived from published sources (Soil and Plant Analysis Council, 2000; Sikora, 2005 and Sikora, 2006) Soil was oven-dried at 38 °C and ground to pass a 2 mm screen. A soil–water paste is created by adding 10 mL of water to 10 cm³ of soil and stirring for with a glass rod and letting stand for at least 15 min but not >2 h. A glass electrode is placed in the mixture to measure pH. After pH measurement, 10 mL of Sikora Buffer (a mixture of triethanolamine, imidazole, MES, acetic acid, and KCl) was added to the soil–water paste and shaken for 10 min. A glass electrode was then placed in the mixture to measure buffer pH within 2 h after shaking. Soil pH and buffer pH were reported as unitless values. Phosphorus, K, Ca, Mg, and Zn are determined in a Mehlich III extract which contains 0.2 N acetic acid, 0.25 N NH₄NO₃, 0.015 N NH₄F, 0.013 N HNO₃, and 0.001 N EDTA. Twenty milliliters of Mehlich III extract is added to 2 cm³ soil, shaken for 5 min, and immediately filtered through Whatman #2 filter paper. Filtration was terminated at the end of 10 min. The filtrate was analyzed via inductively coupled plasma spectroscopy.

Regional determination of abandoned mine and agricultural lands

To calculate the abandoned lands in Kentucky, we analyzed historical data records to identify land use change that had been abandoned from use in agriculture but that had not transitioned to secondary forests, urban areas, aquatic ecosystems such as rivers, streams, and wetlands, or transit infrastructure by methods described by Campbell *et al.* (2008). Mine-lands that

Table 1 Cellulosic ethanol energy production assessment for bioenergy agriculture produced and its contribution to Kentucky's current energy use requirements

	EG	BB	SW
<i>Annual biomass yield potential for Kentucky</i>			
Yield potential for each grass species (kg ha ⁻¹)	14455	10192	12356
Estimated abandoned land yield (65%) (kg ha ⁻¹)	9396	6625	8031
Abandoned mine lands (million ha)	0.3	0.3	0.3
Abandoned ag. (million ha)	1.9	1.9	1.9
Total abandoned land (million ha)	2.2	2.2	2.2
Total arable land (million ha)	5.6	5.6	5.6
Annual yield on abandoned mine land (kg yr ⁻¹)	2.81×10^9	1.99×10^9	2.41×10^9
Annual yield on abandoned agricultural land (kg yr ⁻¹)	1.79×10^{10}	1.26×10^{10}	1.53×10^{10}
Annual yield on total abandoned land (kg yr ⁻¹)	2.07×10^{10}	1.46×10^{10}	1.77×10^{10}
<i>Current annual energy usage in Kentucky (MJ)</i>			
Residential usage (MJ)	3.64×10^{11}	3.64×10^{11}	3.64×10^{11}
Commercial usage (MJ)	2.62×10^{11}	2.62×10^{11}	2.62×10^{11}
Industrial usage (MJ)	9.54×10^{11}	9.54×10^{11}	9.54×10^{11}
Transportation usage (MJ)	5.00×10^{11}	5.00×10^{11}	5.00×10^{11}
Total energy usage (MJ)	2.08×10^{12}	2.08×10^{12}	2.08×10^{12}
<i>Biomass energy yield produced annually compared to usage (MJ)</i>			
Average LCA for native grass biomass produced on marginal land (NEV MJ L ⁻¹)	22.1	21.3	21.6
Energy produced from 1 ha biomass crop (MJ)	1.26×10^5	8.81×10^4	1.10×10^5
Energy produced from biomass grown on total abandoned land (MJ)	2.76×10^{11}	1.93×10^{11}	2.42×10^{11}
Energy produced from biomass grown on total arable land (MJ)	9.84×10^{11}	6.90×10^{11}	8.63×10^{11}
Usage – cellulosic ethanol potential on abandoned land (MJ)	1.80×10^{12}	1.89×10^{12}	1.84×10^{12}
Usage – cellulosic ethanol potential on arable land (MJ)	1.10×10^{12}	1.39×10^{12}	1.22×10^{12}
<i>Potential for bioenergy agriculture to fulfill energy requirements in Kentucky (%)</i>			
Total MJ abandoned land (%)	13.3	9.3	11.7
Total MJ arable land (%)	59.2	41.5	51.9

Yield determinations, agronomic inputs and net energy values (NEV) were generated using data from Stork *et al.* (2009), GREET and EBAMM, land use estimates from Fig. 1 and energy usage from EIA (2007).

were in production and are now in fallow (use of the term fallow is used rather than abandoned because mines have exhausted current economic viability) were estimated based on values for primarily coal and other minor mining activities such as copper, iron, and phosphorous, that are defined in the Kentucky State Abandoned Mine Report for coal (2008) and the Kentucky Mine Mapping Information System (2008), and Kentucky Geological Survey (2007) annual reports for examining enterprise land use shifts other than coal.

Net energy balance of native perennial grass biomass

Agricultural Phase. Energy inputs were for seeding, growing, harvesting, and transporting perennial native grass biomass were calculated using the 'cellulosic' bioenergy agriculture spreadsheet presented by Farrell *et al.* (2006) with values derived from Graboski (2002).

Fertilizer Application. Each plot was fertilized with 67 kg ha⁻¹ nitrogen each spring when plant height

reached 10–20 cm and P and K were maintained at 336 kg ha⁻¹ based on annual soil analysis. Similar to the values defined by Tilman *et al.* (2006), we essentially replaced phosphorus, which constitutes 0.2% of the mass of dry biomass annually harvested, hence approximately 8 kg ha⁻¹ yr⁻¹ on abandoned lands was estimated.

Productivity (yield) loss in degraded land. Life cycle analysis estimate of input and output values generated were mixed between the Stork *et al.* (2009) study site and those defined in the Farrell *et al.* (2006) model and are presented in their raw form in a supplemental online Table (S1). Loss of yield on abandoned land was previously calculated as 60–65% of the managed system (Tilman *et al.*, 2006; Haberl *et al.*, 2007). The Haberl paper suggests that on average (global) the existing agriculture primary production is 65% of what the natural production would be on the same land. Determining the ratio of yields on marginal lands relative to fertile agricultural land contains many

ancillary factors that will influence the measure and currently little data is available on this topic. Tilman *et al.* (2006) used an approach, which reported biomass yield energy of 68 and 111 GJ⁻¹ ha yr⁻¹ on degraded and fertile lands, respectively. This report may be considered a conservative approach, (tending to underestimate yields on marginal lands) because these lands were highly degraded but many of the abandoned agriculture lands might have capacity to have greater yields. Nonetheless, this value provided a 60% degradation rate. Since Kentucky had only 0.3 Mha of marginal mining land compared with 1.9 Mha of marginal agricultural land, our relative estimation of the degradation value was 65% more consistent with Haberl.

Biomass Conversion to Energy. Two scenarios for utilizing native grass biomass for energy were modeled. Biorefinery energy yield potential for the production of bioethanol was performed using LCA for net energy value (NEV) resulting from cellulosic ethanol production via the Farrell *et al.* (2006) estimates, which proposed virtually 100% cellulose conversion. Our own experimental conversion values (without pretreatment) were up to 20% conversion potential (Stork *et al.*, 2009), but pretreatment, albeit energetically costly are available that loosen the lignin–cellulose interaction and subsequently reduce the recalcitrance to enzymatic hydrolysis. Energy yield of biomass conversion to bioelectricity (via co-firing with coal at 0.5% decrease in overall efficiency assuming a 95% coal/5% biomass blend as compared with 100% coal (Yoshitaka, 2005) was generated herein using values obtained for SW (*P. virgatum* L.) pellets that had an energy yield of 18.8 MJ kg⁻¹ (Samson *et al.*, 2008). To calculate the LCA for bioelectricity, we used the Farrell *et al.* (2006) data for the agriculture phase and transportation energy inputs and Stork *et al.* (2009) data for the yield calculation. The co-firing processing energy inputs were calculated using Mani *et al.* (2004) data for grinding and Jannasch *et al.* (2002) data for pelleting and further processing costs were then eliminated from the Farrell *et al.* (2006) spreadsheet (Table S1). After energy cost data was obtained for grinding, pelleting, and agricultural phase this was subtracted from the energy produced on a per kilogram basis. In order to obtain potential for Kentucky, yield data was multiplied by per kilogram energy and total arable as well as abandoned agricultural and mining land. The resulting NEV for bioelectricity was multiplied by crop yield for abandoned land as per above and was then compared with Kentucky's total energy consumption to reach a statewide estimation of bioelectricity potential.

Calculation of net energy potential towards fulfilling regional energy needs. Biomass total was calculated based on the 7-year yield average on a per hectare basis (Stork *et al.*, 2009) and then multiplied by the area of abandoned land within the state of Kentucky. NEV resulting from cellulosic bioenergy was calculated by multiplying the total biomass potential for Kentucky abandoned agricultural and mine land by the NEV obtained in the LCA. Energy usage for commercial, residential, industrial, and transport sectors for Kentucky were obtained from the United States Department of Energy, Energy Information Administration report of Kentucky energy use per sector (2007): energy use per sector and the total energy use was compared with the total NEV for various native perennial grass bioenergy-agriculture systems to provide a relative energy supply to energy demands output.

Greenhouse gas (GHG) costs of biomass energy relative to fossil energy. We considered the total life cycle GHG savings from producing and using biomass to generate biofuels and electricity (Table S1). GHG savings results both from displacing fossil fuels and from the net GHG sequestration. To estimate net GHG savings, we subtract from this amount the total life cycle GHG release from the fossil fuels used to produce prairie biomass and transport it to its point of end use. The soil carbon levels and N₂O emissions are critical to the LCA, and we have clarified our approach to quantifying these components of the life cycle. Soil carbon levels are difficult to quantify and data is scarce for marginal lands. For our analysis, we assume a soil carbon loss [emission of carbon dioxide (CO₂) to the atmosphere] of 0.48 ± 0.44 Mg CO₂ ha⁻¹ yr⁻¹ and N₂O emissions rate of 7.0 kg CO₂e kg N⁻¹ from previous work on monocultures planted on degraded and abandoned agriculture lands (Tilman *et al.*, 2006).

Results

Soil analysis

Reclaimed mine land may be contaminated leading to decreased yield in energy crops. The majority of reclaimed mine land in Kentucky was ex-coal mining enterprise. Therefore, a recently filled mountain top removal coalmine in Pike County, Kentucky (latitude: 37°34'19"N; longitude: 82°44'56"W) was selected as representative and soil samples were obtained and analyzed. These data showed that Meh3 Cd = 0.04 mg kg⁻¹, Meh3 Cr = 0.15 mg kg⁻¹, Meh3 Ni = 1.94 mg kg⁻¹, Meh3 Pb = 1.63 mg kg⁻¹, Meh3 Zn = 2.95 mg kg⁻¹, Meh3 Cu = 1.64 mg kg⁻¹, Meh3 Mo = <0.1 mg kg⁻¹. The pH of the soil was 6.92, phosphorous 7.85 kg ha⁻¹,

potassium 91 kg ha^{-1} , calcium 1185 kg ha^{-1} , magnesium 265 kg ha^{-1} , and Zn levels were 5.7 kg ha^{-1} .

Current land use in Kentucky and land abandonment rates

Kentucky's total land is 10.3 million hectares (Mha), with 5.6 Mha classified as farmland. Of that, only 2.1 Mha are harvested with the other 3.5 Mha of farmland in pasture, rangeland, or woodlands. In addition, 3.5 Mha of forestland is available with most of the land in private ownership. Analysis of land use showed that abandoned agricultural land totaled 1.9 Mha (Fig. 1a) and this was combined with 0.3 Mha of abandoned mine land, of which 0.266 Mha was a direct result of coal mines (Abandoned Mine Report, 2008) and the remainder a mix of mining activities (Kentucky Geological Survey, 2009) (Fig. 1b). Abandoned land was defined as once farmed or mined and is no longer in production and moreover had not entered secondary

ecological succession. Hence, land abandonment rates in Kentucky were determined to currently be 20% of the states land area.

Calculation of net energy potential towards fulfilling regional energy needs

The potential to generate energy from only abandoned land using native plants in the state of Kentucky was determined using yield results derived from a 7-year bioenergy agriculture trial using EG (*T. dactyloides* L.), SW (*P. virgatum*) and BB (*A. gerardii* Vitman) (Stork *et al.*, 2009) and referenced input and output data (Farrell *et al.*, 2006). These data showed that utilizing Kentucky's marginal land to grow native C_4 grasses could yield $2.1 \times 10^{10} \text{ kg yr}^{-1}$ of dry biomass. From currently fallow mine land the potential yield was $2.8 \times 10^9 \text{ kg yr}^{-1}$ of dry biomass. From abandoned agricultural land we determined $1.8 \times 10^{10} \text{ kg yr}^{-1}$ of dry biomass could be grown annually. Using a maximum conversion of cellulose (40% of the plants biomass; Farrell *et al.*, 2006, which is inclusive of hemicellulose) into ethanol and accounting for total life cycle input and output costs, this biomass yield would provide $2.8 \times 10^{11} \text{ MJ}$ of energy per year. Hence, cellulosic ethanol production in a biorefinery could account for an upper end potential of 13.3% of the states 2.08 trillion MJ yr^{-1} requirement for EG and species endemic to Kentucky (Stork *et al.*, 2009) and a lower end of 8.6% for BB grass (Stork *et al.*, 2009) (Table 1, Fig. 2). Using total arable land that is not currently developed as urban areas, transit or waterways and was both currently in food agriculture land use and that defined as abandoned was capable of generating a total of 59% of energy requirements at the upper end of yield estimates from native plants (Fig. 2). The highest yielding EG, SW and BB from our prior study were combined with values derived from GREET (Wang *et al.*, 2007), such as energetic 'cost' of agricultural inputs and those costs associated with the biorefinery stage. Distance from the nearest cellulosic biorefinery was derived based on default distance in EBAMM of 132 miles round trip (Farrell *et al.*, 2006). LCA data showed that the highest NEV for bioenergy agriculture moving through a biorefinery resulting in bioethanol production resulted from EG and was capable of producing 20.9 MJ L^{-1} compared with 19.5 and 20.4 MJ L^{-1} for SW and BB, respectively (Table 1 and Table S1 for raw analysis). It was found that the biorefinery yield maximum was far greater than experimental biorefinery yield (Stork *et al.*, 2009) and resulting NEV, for example using experimental yield $14\,455 \text{ kg ha}^{-1}$ and conversion potential without pretreatment of 0.033 L kg^{-1} compared with 0.26 L kg^{-1} for (Farrell *et al.*, 2006), a NEV of 6.7 MJ L^{-1} was reached.

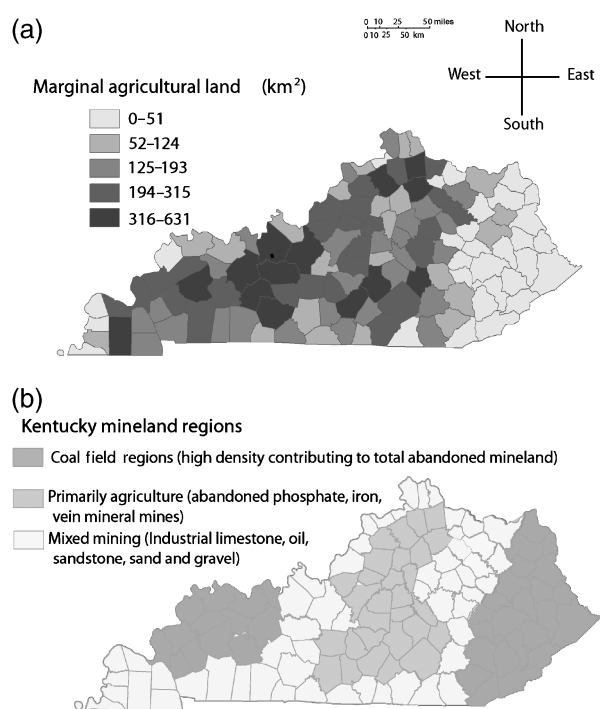


Fig. 1 To scale map of land use displaying current and historical agricultural and mining regions, scale bar displayed within map. (a) Regional and county examination of abandoned agricultural land in Kentucky (km^2) total 1.9 Mha and occur in different densities; (b) regional examination of current and historical mine land adapted from the Kentucky Geological Survey Mineral and Fuel Resources and the Kentucky Department of Mine Reclamation. This map displays the substantial body of land use dedicated to mining of, which 0.3 Mha are classified as historically used.

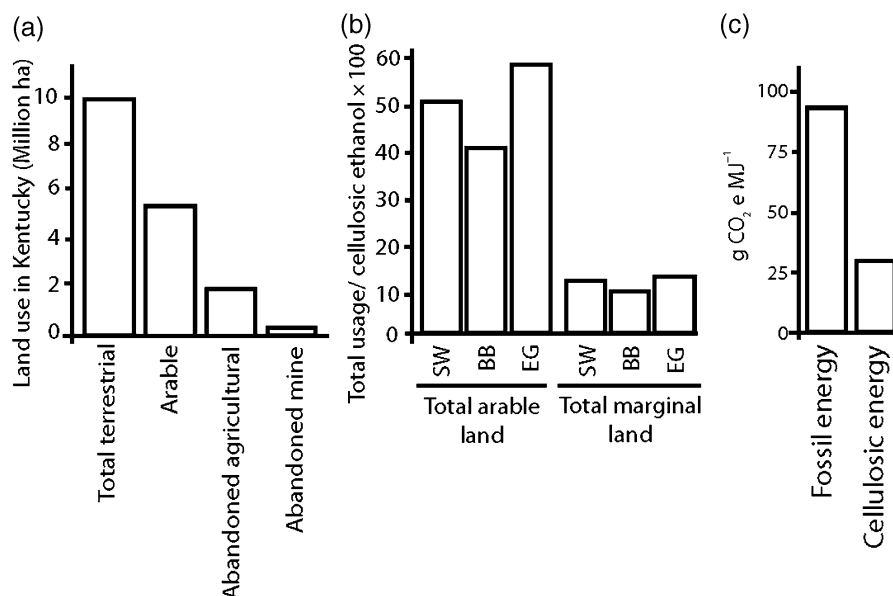


Fig. 2 Land use and potential for bioenergy agriculture using native species to derive energy needs. Data for these calculations was derived from Farrell *et al.* (2006) EIA (2007) and Stork *et al.* (2009). (a) Shows land use quantities for agricultural and marginal land in hectares and (b) shows the relative proportion of Kentucky energy produced by native grasses analyzed in Stork *et al.* (2009) under different land use strategies. Arable land used for bioenergy agriculture vs. marginal land use is depicted. (c) Life cycle assessment of carbon dioxide emissions produced by optimized bioenergy agriculture relative to current fossil energy (gasoline). Data for these calculations was derived from Farrell *et al.* (2006), GREET and Stork *et al.* (2009).

LCA for energy yield of biomass conversion to electricity was generated herein, however, these values were based on values for SW pellets that are currently being blended with coal in Kentucky power plants (70 tons in 2008) and in other states a value of 18.8 MJ kg^{-1} (Samson *et al.*, 2008) was feasible and would eliminate biorefinery processing costs and be replaced by pelletizing and grinding cost (Mani *et al.*, 2004; Jannasch *et al.*, 2002). Based on yield estimates from Stork *et al.* (2009), GREET agricultural input costs and energy cost associated with transport as inputs and the 18.8 MJ kg^{-1} energy yield from cofiring (Porter *et al.*, 2008), we calculate that $3.58 \times 10^{11} \text{ MJ}$ of energy could result from marginal land used for bioenergy agriculture, which represents approximately 17% of the states energy requirements (Table 2). Hence, based on energy production assessment compared between biorefining and cofiring, these data suggest that co-firing yielded 22% more energy than biorefining.

GHG costs of biomass energy relative to fossil energy

Calculation of CO_2 emissions based on the GREET model were confirmatory of previous analysis (Farrell *et al.*, 2006) using yield and input data carried out by Stork *et al.* (2009). These data showed that the cellulosic ethanol bioenergy produced on marginal land was capable of displacing 68% of GHG ($\text{kg CO}_2 \text{ e L}^{-1}$

ethanol) relative to conventional gasoline emission (Fig. 2, Table S2). Moreover, utilizing native grasses to provide this energy would result in greater ecological sustainability due to eliminating the risk of introducing invasive species. Finally, a result of LCA that is difficult to quantify accurately and warrants acknowledgement is that the abandoned agricultural lands that are currently grass are naturally to progress through ecological succession to become forests and in this event will naturally have sequestered carbon. Although it is important, we have not been able to rigorously consider whether the bioenergy agriculture results in greater carbon offsets than natural succession.

Discussion

Currently, renewable energy such as wind, solar photovoltaic cells and biomass account for <7% of the United States energy consumption (Wald, 2007). In this context, looking carefully at regional energy policy will be important for determining how this number can be sustainably increased. Herein, an LCA was used for the quantitative determination of fossil energy replacement by marginal land bioenergy agriculture in the high land abandonment state of Kentucky. We found that marginal land accounted for 21% of the states land mass. This was consistent with previous predictions of global marginal land use for bioenergy agriculture

Table 2 Cellulosic cofiring energy production assessment for bioenergy agriculture produced and its contribution to Kentucky's current energy use requirements

	EG	BB	SW
Yield kg ha ⁻¹ (Stork <i>et al.</i> , 2009)	9396	6625	8031
Potential yield on abandoned land kg	2.07×10^{10}	1.46×10^{10}	1.77×10^{10}
Energy from cofiring			
Energy from cofiring biomass from total arable land (MJ)	1.53×10^{12}	1.08×10^{12}	1.31×10^{12}
Energy from cofiring biomass from total abandoned land (MJ)	3.89×10^{11}	2.74×10^{11}	3.32×10^{11}
Energy consumption (Kentucky)	2.08×10^{12}	2.08×10^{12}	2.08×10^{12}
Cofiring bioenergy (arable land)/consumption $\times 100$ (%)	69.2	46.7	57.4
Cofiring bioenergy (abandoned land)/consumption $\times 100$ (%)	17.2	11.9	14.6
Agricultural phase energy loss (GREET, EBAMM) (MJ ha ⁻¹)	8172		
Cofiring processing energy usage (MJ kg ⁻¹)(sum of ^a)	0.63		
^a Transportation from field to powerplant (MJ kg ⁻¹)	0.26	GREET, Campbell <i>et al.</i> (2009)	
^a Pelletizing (MJ kg ⁻¹)	0.27	Jannasch <i>et al.</i> (2002)	
^a Grinding (MJ kg ⁻¹)	0.10	Mani <i>et al.</i> (2004)	
Agricultural phase inputs (arable land, MJ)	7.08×10^{10}	7.08×10^{10}	7.08×10^{10}
Agricultural phase inputs (abandoned land, MJ)	1.80×10^{10}	1.80×10^{10}	1.80×10^{10}
Cofiring processing inputs (arable land, transport and pelleting, MJ)	4.89×10^{10}	3.59×10^{10}	4.32×10^{10}
Cofiring processing inputs (abandoned land, transport and pelleting, MJ)	1.29×10^{10}	9.12×10^9	1.11×10^{10}
Net energy output (arable land, MJ)	1.44×10^{12}	9.72×10^{11}	1.19×10^{12}
Net energy output (abandoned land, MJ)	3.58×10^{11}	2.47×10^{11}	3.03×10^{11}

Yield determinations, agronomic inputs and net energy values (NEV) were generated using data from Stork *et al.* (2009), Campbell *et al.* (2009), Mani *et al.* (2004), Jannasch *et al.* (2002), GREET and EBAMM, land use estimates from Fig. 1 and energy usage from EIA (2007).

(Campbell *et al.*, 2008). These authors predicted that 8% of world energy can be produced by biomass. Broadly, herein we will exemplify a scenario for carbon mitigating bioenergy agriculture in Kentucky, as an upper limit region, and demonstrate that 21% of the states land could fulfill 13.3% (Fig. 2b) of current energy consumption by optimized biorefinery processes and 17% by simple co-firing and upgrading of coal fired electricity plants (Tables 1 and 2).

It is prudent to note that even using all of the available arable land in Kentucky for biorefinery-based energy production, at the expense of land use for food agriculture, we accounted for just over 59% of Kentucky's energy needs and such a situation would not be sustainable. Energy derived from marginal land does not compete with food production land-use and is expected to both be socially and environmentally friendly and also bolster rural economic development (Farrell *et al.*, 2006). Kentucky has a relatively long growing season with significant rainfall that could produce sizeable quantities of perennial herbaceous and woody biomass. But, we are utilizing marginal agricultural, abandoned or reclaimed mine land, and select primary ecological succession woodland areas that have unique challenges related to establishing,

growing, harvesting, and transporting the crops from the land to an end user (Tilman & Downing, 1994). Overcoming these challenges in the coming decade will be an important goal. Moreover, land use change on the order of 20% of the states surface area will require careful examination of the plant type used for invasive potential. This is particularly true for *Miscanthus* species, which although have a potential to produce much greater yield than other grass species 60 tons ha⁻¹ yr⁻¹ reported by Heaton *et al.* (2008) compared with 27 tons ha⁻¹ yr⁻¹ for any single variety and year growing native grasses in Kentucky (Stork *et al.*, 2009). Sterile *Miscanthus* \times *giganteus* entries have been proposed for bioenergy agriculture, however, these reproduce vegetatively by rhizomes and are extremely vigorous characteristic invasive plants (Raghu *et al.*, 2006) and therefore should not be assumed to be risk free. In fact, many pristine areas in Kentucky already have invasive outbreaks of *Miscanthus* and the Bernheim Arboretum and Nature Conservancy of Kentucky consider it among the top 5 invasive plants to the state (J.Lumpe, personal communication). These risks may be manageable and if so, even a doubling of yield could account for one-third of Kentucky's energy consumption using marginal land. Moreover, native plants that are bred for

vigor may also display invasive behavior and should be carefully assessed. Native and mixed plants species have been shown to build robustness into agro-ecosystems (Raghu *et al.*, 2006; Smith *et al.*, 2008) and may therefore gain from intensive breeding and research efforts to improve and select for yield traits.

Contaminants in restored mine sites can reduce plant productivity (Merry *et al.*, 1985) and edible plants can sequester toxic amounts of contaminants that bioaccumulate in an ecosystem (Murillo *et al.*, 1999). Therefore, we performed soil composition analysis on a restored mine site from a mountain top removal mine in Eastern Kentucky since the vast majority (87%) of reclaimed mine land in Kentucky was once coal based. A coal mine site that had been restored in the past 5 years was selected where topsoil replacement technique that are required in Kentucky were abided by. Results did not support the postulate that heavy metal contamination would reduce plant productivity and we concluded that improved N, P, and K ratios were needed, but further studies are needed in this area. Research that has been performed on such sites (Ashby, 1997) found that compaction more so than contamination plays a role in limiting vegetation growth.

Data provided herein were unable to account for ancillary improvements in energy efficiency technology, both in residential and transportation, which may ultimately provide the best means to reduce reliance on fossil fuels. Nor do these data account for gains in economic sustainability associated with bioenergy-agriculture-based rural economic development. With respect to the three pillars of sustainability; social pillars were upheld by a proportion of energy needs; economic pillars by rural economic development and the horizontal and vertically integrated industries providing infrastructure; environment pillars by producing renewable, carbon mitigating energy using native plants. But, between 83% and 87% of energy needs are unaccounted for using our abandoned land for bioenergy agriculture ethanol or bioelectricity production. It is therefore evident that further renewable forms of energy or enormous leaps in efficiency technology will be needed to supplement current energy needs and transition from fossil to renewable energy. Moreover, the findings of this study suggest that regional examination of native energy crops may have utility in selecting feedstock's for bioenergy agriculture that are both well adapted to meteorological conditions and have high yield and bioenergy conversion potential.

Acknowledgements

This article is published with approval of the Director of the Kentucky Agricultural Experiment Station as article number

(09-11-067). Funding was provided to SD by NSF: IOS-0922947 and NSF: EFRI-0937657 and as start up funds from UK College of Agriculture.

References

- Ashby CW (1997) Soil ripping and herbicides enhance tree and shrub restoration on stripmines. *Restoration Ecology*, **5**, 169–177.
- Boddiger D (2007) Boosting biofuel crops could threaten food security. *The Lancet*, **370**, 923–924.
- Brookings Institute Per capita carbon emissions from transportation and residential energy use. (2005) Available at http://www.brookings.edu/reports/2008/~media/Files/rc/papers/2008/05_carbon_footprint_sarzynski/tables.pdf.
- Campbell JE, Lobell DB, Genova RC, Field CB (2008) The global potential of bioenergy on abandoned agriculture lands. *Environmental Science and Technology*, **42**, 5791–5794.
- Campbell JE, Lobell DB, Field CB (2009) Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science*, **324**, 1055–1057.
- Energy Information Administration (2007) USDOE, Energy Information Administration, Washington, DC. Available at <http://www.eia.doe.gov/oiaf/aeo/> (Accessed March 2009).
- Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. *Science*, **311**, 506–508.
- Graboski MS (2002) *Fossil Energy Use in the Manufacture of Corn Ethanol*. National Corn Growers Association, St. Louis, MO.
- Haberl H, Erb KH, Krausmann F *et al.* (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 12942–12945.
- Heaton EA., Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of *Miscanthus*. *Global Change Biology*, **14**, 2000–2014.
- Jannasch R, Quan Y, Samson R (2002) *A Process and Energy Analysis of Pelletizing Switchgrass*, Final Report. Resource Efficient Agricultural Production (REAP-Canada), Anne de Bellevue, QC.
- Kentucky State Abandoned Mine Report (2008) Twenty-Sixth Annual Evaluation Summary Report for the Regulatory and Abandoned Mine Land Reclamation Programs Administered by the Commonwealth of (2008) *Kentucky* 36. Office of Surface Mining Reclamation and Enforcement Kentucky, Frankfort, KY, pp. 46–48.
- Kentucky Geological Survey (2009) Geospatial data library. Available at http://www.uky.edu/KGS/gis/kgis_gis.html.
- Mani S, Tabil LG, Sokhansanj S (2004) Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. *Biomass and Bioenergy*, **35**, 339–352.
- Merry RH, Tiller KG, Alston AM (1985) The effects of contamination of soil with copper, lead and arsenic on the growth and composition of plants. *Plant and Soil*, **91**, 115–121.
- Murillo JM, Maranon T, Cabrera F, Lopez R (1999) Accumulation of heavy metals in sunflower and sorghum plants affected by the Guadamar spill. *The Science of the Total Environment*, **242**, 281–292.

- Piñeiro G, Jobbágy EG, Baker J, Murray BC, Jackson RB (2009) Set-asides can be better climate investment than corn ethanol. *Ecological Applications*, **19**, 277–282.
- Raghu S, Anderson RC, Daehler CC, Davis AS, Wiedenmann RN, Simberloff D, Mack RN (2006) *Science*, **313**, 1742.
- Samson R, Lem CH, Stamler SB, Dooper J (2008) Developing Energy Crops for Thermal Applications: Optimizing Fuel Quality, Energy Security and GHG Mitigation. In *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*. (ed. D Pimental) Springer Science, Berlin, Germany, 395–423.
- Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.
- Sikora FJ (2005) *Replacing SMP buffer with Sikora buffer for determining lime requirement of Soil*. A Technical Review.
- Sikora FJ (2006) A buffer that mimics the SMP buffer for determining lime requirement on soil. *Soil Science Society of America Journal*, **70**, 474–486.
- Smith P, Martino D, Cai Z *et al.* (2008) Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society, B*, **363**, 789–813.
- Soil and Plant Analysis Council (2000) Chapter 3. Soil pH, and exchangeable acidity and aluminum. Chapter 6. Phosphorus. Chapter 7. Major cations (potassium, calcium, magnesium, and sodium). Chapter 8. Micronutrients (boron, copper, iron, manganese, and zinc). In: *Soil analysis handbook of reference methods*. Soil and Plant Analysis Council Inc., CRC Press, Boca Raton, FL.
- Stork J, Montross M, Smith R *et al.* (2009) Regional examination shows potential for native feedstock options for cellulosic biofuel production. *Global Change Biology Bioenergy*, **1**, 230–239.
- Tilman D, Downing JA (1994) Biodiversity and stability in grasslands. *Nature*, **367**, 363–365.
- Tilman D, Hill J, Lehman C (2006) Biodiversity and ecosystem stability in a decade-long grassland experiment. *Science*, **314**, 1598–1600.
- Twenty-Sixth Annual Evaluation Summary Report for the Regulatory and Abandoned Mine Land Reclamation Programs Administered by the Commonwealth of 2008 Kentucky 36. Office of Surface Mining Reclamation and Enforcement Kentucky, Frankfort, KY, pp. 46–48.
- Wald ML (2007) The power of renewables. *Scientific American*, **300**, 57–61.
- Wang M, Wu Y, Elgowainy A (2007) *Operating Manual for GREET: Version 1.7*. Argonne National Laboratory, Argonne, IL.
- Yoshitaka T (2005) Coal and woody-biomass co-firing technology in large scale boilers. *Journal of the Japan Boiler Association*, **332**, 22–30.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Cellulosic biofuel from eastern gamagrass.

Table S2. CO₂ calculator (GHG emissions).

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.